

The empirical upper limit for mass loss of cool main sequence stars

Anna Lednicka and K. Stępień

Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
email: lednicka@astrouw.edu.pl, kst@astrouw.edu.pl

Received ...; accepted ...

ABSTRACT

Context. The knowledge of mass loss rates due to thermal winds in cool dwarfs is of crucial importance for modeling evolution of physical parameters of main sequence single and binary stars. Very few, sometimes contradictory, measurements of such mass loss rates exist up to now.

Aims. We present a new, independent method of measuring an amount of mass lost by a star during its past life.

Methods. It is based on the comparison of the present mass distribution of solar type stars in an open cluster with the calculated distribution under an assumption that stars with masses lower than M_{lim} have lost an amount of mass equal to ΔM . The actual value of ΔM or its upper limit is found from the best fit.

Results. Analysis of four clusters: Pleiades, NGC 6996, Hyades and Praesepe gave upper limits for ΔM in three of them and the inconclusive result for Pleiades. The most restrictive limit was obtained for Praesepe indicating that the average mass loss rate of cool dwarfs in this cluster was lower than $6 \times 10^{-11} M_{\odot}/\text{yr}$. With more accurate mass determinations of the solar type members of selected open clusters, including those of spectral type K, the method will provide more stringent limits for mass loss of cool dwarfs.

Key words. stars: activity – stars: late-type – stars: mass loss – stars: winds, outflows

1. Introduction

Chromospheric-coronal activity is ubiquitous in cool stars possessing subphotospheric convection zones. Hot coronas result in existence of thermal winds carrying away stellar mass and angular momentum. The precise knowledge of the mass loss rate (MLR) during the stellar life is of crucial importance for modeling evolution of mass, luminosity and rotation of single stars and of orbital parameters of close binary stars. Mass loss of a central star of a planetary system may also influence evolution of physical parameters of orbiting planets. Proximity of the Sun made possible direct measurements of solar wind with the use of interplanetary probes. The average velocity of the wind near the Earth orbit is of the order of 400 km s^{-1} and the average MLR is $2 \times 10^{-14} M_{\odot}/\text{yr}$ with uncertainty of some 50 % (Feldman et al. 1977). The expected MLRs for other cool dwarfs may differ from that at most by a couple of orders of magnitude but even the highest MLRs of such stars are far lower than those occurring in hot, early type stars or red giants. The present observational capabilities are still insufficient to obtain the data for other dwarfs with comparable to the solar case accuracy. For many years only indirect methods of MLR estimate of such stars existed. Analyzing the infrared and radio observations of M dwarfs Mullan et al. (1992) obtained a value of $10^{-10} M_{\odot}/\text{yr}$ as an upper limit for MLR of these stars. Later, van den Oord & Doyle (1997) revised that limit down to $10^{-12} M_{\odot}/\text{yr}$. A similar value was obtained by Lim & White (1996). Wargelin & Drake (2002) obtained an upper limit of $3 \times 10^{-13} M_{\odot}/\text{yr}$ for *Proxima* Cen. In the recent years Wood and coworkers published a number of papers in which they analyzed profiles of L_{α} arising at the collisional front between stellar wind and interstellar mat-

ter. By modeling the collision process the authors were able to measure MLRs for a dozen stars (Wood et al. 2002, 2005). The measured rates extend from $2 \times 10^{-12} M_{\odot}/\text{yr}$ for 70 Oph down to $3 \times 10^{-15} M_{\odot}/\text{yr}$ for DK UMa. The authors derived a relation between MLR and age (or X-ray flux). Their latest results give $\dot{M} \propto t^{-2.33}$ for $t \geq 0.7 \text{ Gyr}$ but observations of younger, more active stars suggest a sudden drop of MLR from about 2×10^{-12} to $\sim 10^{-13} M_{\odot}/\text{yr}$, i. e. by more than an order of magnitude. This unexpected result is based on scanty data and needs confirmation. A different, indirect method of estimation an amount of mass lost by the Sun during its past life was suggested by Sackmann & Boothroyd (2003). Based on the geological evidence that the terrestrial atmosphere was warm in early life of the Solar System and liquid water was present on Mars, they calculated the minimum initial mass of the Sun needed to produce enough luminosity, and reconstructed time variation of the solar MLR so adjusted that the favorable thermal conditions on the Earth and Mars have been kept as the Sun aged. The optimum conditions were reproduced for the initial mass of $1.07 M_{\odot}$ and MLR decreasing exponentially with time.

Here we present another method of measuring the total amount of mass lost during the stellar life. It is based on the analysis of the stellar mass distribution in an open cluster. The next section describes details of the suggested method. The last section contains discussion of the results and conclusions.

2. Method

2.1. General considerations

The total energy flux carried away with the stellar wind, F_{tot} , consists of three components (Holzer 1987)

$$F_{\text{tot}} = F_{\text{grav}} + F_{\infty} + F_{\text{rad}}, \quad (1)$$

where F_{grav} is the energy flux needed to carry the wind matter out of the potential well of the star, F_{∞} is the kinetic energy flux of the wind in infinity and F_{rad} is the flux radiated away by the wind. Based on observations of the solar wind F_{rad} can be neglected. We thus obtain

$$F_{\text{tot}} = \frac{1}{2} \dot{M} (v_{\text{esc}}^2 + v_{\infty}^2) \approx \dot{M} v_{\text{esc}}^2, \quad (2)$$

where v_{esc} is the escape velocity from the stellar surface and v_{∞} is the wind velocity in infinity. The last approximate equality results from the assumption that both velocities are of the same order. With $v_{\text{esc}} = (2GM/R)^{1/2}$, where G is gravitational constant, and M and R are stellar mass and radius, respectively, we have

$$F_{\text{tot}} = \frac{2GM\dot{M}}{R}. \quad (3)$$

The ultimate source of energy for thermal winds in cool stars is stellar luminosity which drives convection and, via a chain of physical processes, makes a magnetized wind to blow. Rotational energy, albeit necessary for magnetic field generation (dynamo does not work in nonrotating stars), is of secondary importance. If so, the total energy flux of the wind can be expressed as a fraction kL of stellar luminosity

$$\dot{M} = 1.5 \times 10^{-8} \frac{kLR}{M} \quad (4)$$

where M , R and L are in solar units and \dot{M} is expressed in solar mass per year. The observed solar value of MLR gives $k_{\odot} = 1.3 \times 10^{-6}$. For comparison, Kudritzki & Reimers (1978) derived an empirical relation for M-type giants

$$\dot{M} = 5.5 \times 10^{-13} \frac{LR}{M}, \quad (5)$$

from which $k_{\text{MG}} = 3.7 \times 10^{-5}$. Surprisingly, although MLRs of M-giants are some 7 orders of magnitude higher than the solar value, the efficiency factor k_{MG} , describing the transformation of the red giant radiation into wind energy, is only about 30 times higher than k_{\odot} .

How high values can MLR reach in the most active cool dwarfs? Stars with X-ray emission at the saturated level have $L_x \approx 10^{-3}L$ and if we apply the same efficiency factor to MLR (i. e. $k = 10^{-3}$) we obtain an upper limit of $1.5 \times 10^{-11} M_{\odot}/\text{yr}$ for a one solar mass star. The upper limit drops, however, sharply for lower mass stars due to a fast decrease of their luminosity and reaches a value of $7 \times 10^{-13} M_{\odot}/\text{yr}$ for a 0.4 solar mass star. (Note that, according to the results of Wood et al. 2005, the proportionality between MLR and X-ray luminosity breaks down for the most active stars). This brief discussion indicates that the expected MLR of active solar type stars should not considerably exceed $\sim 10^{-11} M_{\odot}/\text{yr}$ and yet it may be significantly lower if the results of Wood et al. (2005) are confirmed.

2.2. Method of the mass loss estimate

Initial mass distribution of a stellar cluster is well described by the Salpeter function (Salpeter 1955). Recent discussion of this distribution by Kroupa (2002) showed, as the author stresses, that the initial mass function of different populations of stars shows an extraordinary uniformity and is well described by the Salpeter function, contrary to the simple minded reasoning that it should vary with star-forming conditions. The Salpeter mass distribution is given by

$$\frac{dN}{dM} \propto M^{-\alpha}, \quad (6)$$

where dN is a number of stars with masses between M and $M + dM$. Values of α determined for individual star aggregates in the intermediate mass range concentrate around the original Salpeter value $\alpha = 2.35$ with a scatter expected from statistics (Elmegreen 2001).

The mass distribution evolves with the cluster age due to different dynamical effects, like evaporation of low-mass stars and stellar evolution affecting mostly high-mass stars. The mass distribution of solar type stars (with masses, say, between 0.5 and 2 M_{\odot}) is expected to be least affected by the above mentioned effects. It will, however, evolve due to mass loss via thermal wind from stars with subphotospheric convection zones. Let us assume that the mass distribution of solar type stars with $M > M_{\text{lim}}$ has not changed during the past cluster life but stars with $M \leq M_{\text{lim}}$ have lost an amount of mass equal to ΔM . The assumption is justified by the sharp rise of coronal activity at mid-F spectral type and, equally sharp, drop of stellar rotation velocity around the same type, indicating a sudden appearance of magnetized winds over a narrow spectral range (Schmitt 1997; Gray 2005). Let ΔM be independent of mass. A gap in the mass distribution then occurs just below M_{lim} with a width of ΔM and, at the same time, the distribution function for lower mass stars will run lower than the initial function. Fig 1 shows the initial (Salpeter) mass distribution and two distributions modified by mass loss of 0.1 and 0.3 M_{\odot} when $M_{\text{lim}} = 1.25 M_{\odot}$. The second value of ΔM is probably unrealistically high but it is shown here to emphasize the expected distribution modifications.

There are indications that the bulk of mass loss occurs when stars are young and active i. e. younger than about 1 Gyr. The time-scale of spin-down of young, rapidly rotating stars is about $1 - 2 \times 10^8$ years (Stępień 1988) which means that after several hundred Myr the activity drops considerably. The observations of stellar X-ray activity by Güdel, Guinan & Skinner (1997) show, indeed, that the activity decreases by about 1.5 order of magnitude during the first Gyr of stellar life. These results indicate that the optimum cluster age for the analysis of ΔM is from several hundred Myr, up to about 1 Gyr. Stars in very young clusters have not had enough time to lose an appreciable amount of mass whereas ΔM in old clusters is expected to increment negligibly with age due to a decrease of MLR down to the solar value or even beyond. At the same time, mass distribution of an old cluster becomes notably perturbed by other effects, like evaporation of low mass stars and evolution of massive stars. With ΔM known, the *average* MLR can be estimated: $\dot{M}_{\text{av}} = \Delta M/T$, where T is the cluster age.

Unfortunately, accurate mass values of solar mass members are presently known only for very few clusters in the optimum age range. We selected four clusters for the analysis: Hyades, Praesepe, Pleiades and NGC 6996. Masses of Hyads were determined by Perryman et al. (1998). Later analysis by de Bruijne, Hoogerwerf & de Zeeuw (2001) confirmed these

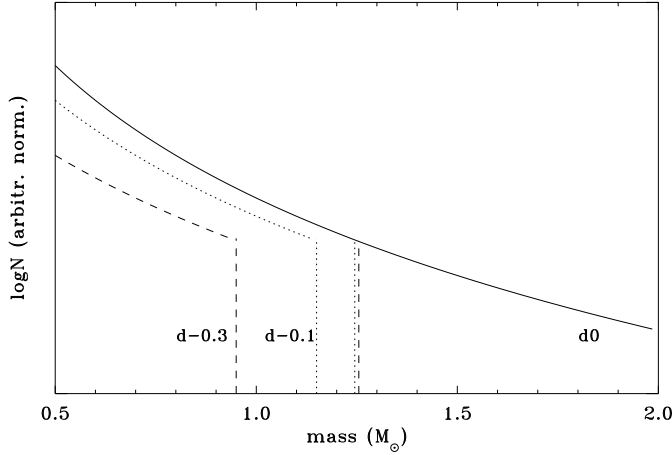


Fig. 1. Expected differences among stellar mass distributions in a cluster, resulting from the assumed mass loss: solid line, labelled d0 - no mass loss; dotted line, labelled d-0.1 - mass loss of $0.1 M_{\odot}$ in stars with $M < 1.25 M_{\odot}$; broken line, labelled d-0.3 - mass loss of $0.3 M_{\odot}$ in the same stars. All three distributions have a common part for stars with $M \geq 1.25 M_{\odot}$ (the vertical dotted and dashed lines at $M = 1.25 M_{\odot}$ are slightly displaced from their exact positions for better visibility). Note a gap in two latter distributions, broadening with the increased mass loss.

values. Perryman et al. (1998) give masses for 218 stars. After rejecting all giants, variables and stars marked by de Bruijne et al. (2001) as nonmembers, 133 dwarfs were left. Data on stellar masses of Praesepe and Pleiades were taken from Raboud & Mermilliod (1998a, b). The authors selected 185 members of Praesepe and 270 members of Pleiades and determined their masses from colors using isochrones with metallicity $Z = 0.02$. Masses of known binary components were determined as described by Raboud & Mermilliod (1998a). No published masses for members of NGC 6996 exist so we computed them using *UBV* photometry of Villanova et al. (2004). The following values of the parameters, needed to convert the observations into absolute photometry, were adopted: distance moduli 9.4 mag, $E(B - V) = 0.54$ and $A_V = 3E(B - V)$. Bolometric corrections were applied following Bessel, Castelli & Plez (1998). Individual masses were calculated from the relation (Lang 1992)

$$\log\left(\frac{M}{M_{\odot}}\right) = 0.263 \log\left(\frac{L}{L_{\odot}}\right) - 0.021. \quad (7)$$

Photometric errors result in $\pm 0.05 M_{\odot}$ random mass errors. The errors of absolute values of stellar masses are likely to be larger, due to probable systematic errors, but the uncertainties of the *relative* mass determinations should be close to those resulting from photometry. Errors of mass determination of single stars in the other analyzed clusters are assumed to be of the same order i. e. $\pm 0.05 M_{\odot}$. In case of resolved binaries with no spectroscopic orbits expected errors are several times larger. Unresolved binaries present another problem. They enter the analysis as single objects instead of two stars, producing thus a bias in the observed mass distribution. Fortunately, the commonly employed methods of detecting binaries are most sensitive to systems with similar components, i.e. when mass ratio q is close to 1. As a result, frequency of known binaries among solar type stars in the investigated clusters is as high as, or higher than, among nearby field stars for which binary searches are be-

Table 1. Results of a comparison of the calculated and observed mass distributions. The compared distributions are identical at the significance level of 5% if statistic $\lambda \leq \lambda_{\text{lim}} = 1.36$.

Cluster	ΔM	λ	Cluster	ΔM	λ
Pleiades	0	2.18	Hyades	0	0.58
	0.1	2.96		0.1	0.93
	0.2	3.81		0.2	1.42
NGC 6996	0	0.55	Praesepe	0	1.08
	0.1	1.05		0.1	1.75
	0.2	1.58		0.2	2.62

lieved to be nearly complete (Halbwachs et al. 2004). This indicates that in well studied clusters the percentage of missing binaries with *both* component masses from the considered mass range $[0.5, 2.0] M_{\odot}$ is low, except, possibly, in the cluster central regions where crowding of stellar images makes analysis more difficult. A stronger bias is expected among low q binaries with a solar type primaries and very low mass secondaries. Only primaries enter the statistics and secondaries are missing, which produces a deficit in the lowest mass tail of mass distribution (Kroupa 1995). Such a deficit does not matter in our case as long as we restrict the analysis to solar type stars only.

We assume conservatively that two mass distributions differing in ΔM by less than $0.05 M_{\odot}$ are statistically indistinguishable, so if for example the original Salpeter function correctly describes the observed distribution of a given cluster, we adopt $0.05 M_{\odot}$ as an upper limit for mass loss of its solar type members.

The observed mass distribution in each analyzed cluster was binned in $0.1 M_{\odot}$ wide intervals. Multiple star components with known masses were treated as single stars. The calculated distribution, corresponding to a given value of mass loss, was calibrated against the mass interval $1.25 - 2.0 M_{\odot}$ and its part corresponding to $M \leq 1.25 M_{\odot}$ was compared to the observations. The Kolmogorov-Smirnov test was applied to verify a null hypothesis that the calculated distribution is identical with the observed one in this mass interval. The test uses the statistic λ (sometimes denoted by D_n) describing the maximum difference between the empirical and the given (theoretical) cumulative distribution functions. We adopted the significance level of 5% which corresponds to the statistic $\lambda \leq \lambda_{\text{lim}} = 1.36$. The procedure was applied to the Salpeter function and the distributions with a few values of ΔM . The results are shown in Table 1.

3. Results

3.1. Comparison of the calculated mass distributions to observations

Assuming that solar type members of a given cluster have lost ΔM_{cl} mass over their past life, we expect the function $\lambda(\Delta M)$ to reach a minimum $\lambda = \lambda_{\text{min}}$ at $\Delta M = \Delta M_{\text{cl}}$. If the condition $\lambda_{\text{min}} \leq \lambda_{\text{lim}}$ is fulfilled we assume that ΔM_{cl} is the most probable value of the amount of mass lost by the cluster members although any value of ΔM from the neighbourhood of ΔM_{cl} is also possible as long as $\lambda(\Delta M) \leq \lambda_{\text{lim}}$. The latter condition determines the uncertainty of the obtained mass loss. Its rigid application may, however, result in an underestimation of actual uncertainty of ΔM_{cl} when λ_{min} is only barely lower than λ_{lim} and $\lambda(\Delta M)$ quickly exceeds λ_{lim} for ΔM moving away from ΔM_{cl} . To obtain a more realistic measure of the actual accuracy of ΔM_{cl} both, a depth and a shape of the λ minimum should be considered. A deep, sharp minimum with λ rising rapidly away from it

means that ΔM_{cl} is well determined with a high degree of confidence. A broad, shallow λ minimum means that the value of ΔM_{cl} is poorly constrained.

Table 1 shows that λ_{min} is reached for $\Delta M = 0$ for all the investigated clusters, which means that only an upper limit for the mass loss of each cluster can be determined. In case of Pleiades – the youngest of the discussed clusters (see Table 2), even the distribution with $\Delta M = 0$ poorly describes the observed distribution. This may be connected with an apparent deficit of massive stars among the presently observed members (Moraux et al. 2004). Fig. 2 shows the observed distributions of all four clusters with the Salpeter function overplotted. For NGC 6996 and Hyades the distributions with $\Delta M = 0.1 M_{\odot}$ also describe satisfactorily the observed distributions at the assumed significance level so the upper limit for mass loss in these clusters is equal to $0.15 M_{\odot}$. Note, however, that in case of Hyades the rise of $\lambda(\Delta M)$ is so slow that a value of $0.20 M_{\odot}$ only weakly violates the 5 % condition, so the limit of $0.25 M_{\odot}$ is nearly equally probable as $0.15 M_{\odot}$. The same limit of $0.25 M_{\odot}$ was obtained from a comparison of the calculated distributions to observations of 90 single Hyads with best known masses, carefully selected by de Bruijne et al. (2001). Finally, only the Salpeter function describes satisfactorily the mass distribution in Praesepe and the rise of $\lambda(\Delta M)$ is quite sharp (Table 1). While the probability of occurring $\lambda \geq 1.08$ is about 0.20, it drops to less than 0.01 for $\lambda \geq 1.75$. We adopt a value of $0.05 M_{\odot}$ as an upper limit for mass loss in this cluster. Dividing the upper limit by the cluster age we obtain an upper limit for an average MLR over the past cluster life. The results (together with the adopted ages) are shown in Table 2.

As we see, the derived MLRs in NGC 6996 and Hyades are not very restrictive. However, the upper limit for mass loss and MLR in Praesepe look interesting. The maximum mass loss is lower than the solar mass loss of $0.07 M_{\odot}$ determined by Sackmann & Boothroyd (2003). The maximum MLR is close to the theoretically estimated upper limit (see above) and is lower than some of the empirical determinations (e.g. Mullan et al. 1992).

The result for Praesepe demonstrates a potential usefulness of the suggested method. The presently attained accuracy of the method is limited by two main factors: the accuracy of mass determination and scarcity of data, particularly for lower mass members. The present mass determinations extend only to $M \sim 0.8 M_{\odot}$. Deeper surveys, including stars of spectral type K, i.e. down to $0.5 M_{\odot}$, are needed, together with an increased accuracy of mass determination. When masses of stars from the spectral range A-K in stellar clusters with age ~ 1 Gyr are known with relative accuracy of $0.01-0.02 M_{\odot}$, it will be possible to detect average MLRs at the level of $\sim 10^{-11} M_{\odot}$ or less. Such an accuracy should be possible to reach with new generation instruments, like LSST, Gaia and fibre-fed multiobjects spectrographs. The residual unresolved binaries will add to the observational noise smearing the notch in the predicted mass distribution (Fig. 1). Fortunately, the Kolmogorov-Smirnov test is only weakly sensitive to such an effect.

Systematic errors may be larger but this does not hurt – such errors influence only absolute mass determinations which are irrelevant here. Moreover, they can be offset by adequately varying the value of the limiting mass for mass loss to occur. If the future data are accurate enough to detect a possible change of the slope of the mass distribution with age it may be possible to analyze mass dependence of MLR. This, however, needs a further increase of accuracy of mass determination and an extension of the observed mass distribution to still lower masses.

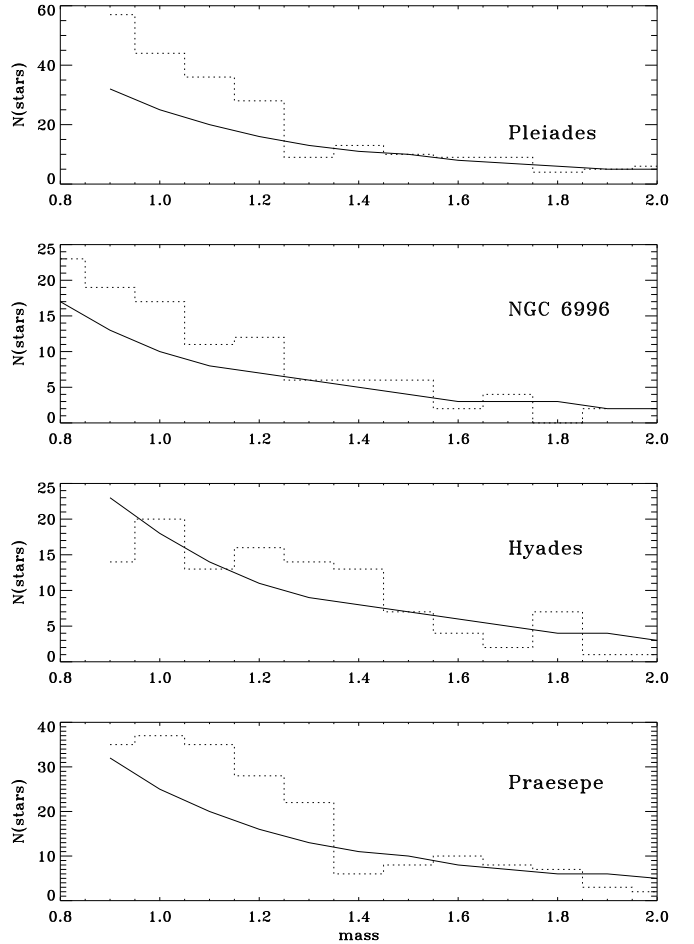


Fig. 2. The observed mass distributions in three clusters with the Salpeter functions overplotted. The Salpeter function is normalized in each case to the distribution of stars with masses from the interval $1.25-2.0 M_{\odot}$.

Table 2. Upper limits for mass loss and the resulting upper limits for average MLRs of stars in the investigated clusters.

Cluster	Age Myr	Max. mass loss M_{\odot}	Max. average MLR $10^{-11} M_{\odot}/\text{yr}$
Pleiades	100	?	?
NGC 6996	325	0.15	43
Hyades	625	0.15-0.25	24-40
Praesepe	832	0.05	6

3.2. Conclusions

A new method of mass loss determination in cool dwarfs is presented. It is based on a comparison of the observed mass distribution in a stellar cluster with a distribution modified by an assumed mass loss ΔM occurring during the cluster past life. The method was applied to four open clusters with ages between 100 Myr and 1 Gyr. The most significant result was obtained for Praesepe for which an upper limit of $0.05 M_{\odot}$ for ΔM was determined. From the age of the cluster an upper limit for average MLR can be calculated. It is equal to $6 \times 10^{-11} M_{\odot}/\text{yr}$. This is a promising result. With more complete surveys of cluster members and better mass determinations, a significantly better estimate will be obtained.

Acknowledgements. We thank an anonymous referee for very helpful comments. This work was partly supported by the Ministry of Science and Higher Education grant 1 P03 016 28.

References

- Bessel, M.S., Castelli, F., Plez, B.: 1998, *A&A* 333, 231
- de Bruijne, J.H.J., Hoogerwerf, R., de Zeeuw, P.T.: 2001, *A&A* 367, 111
- Elmegreen, B.G.: 2001, in: *From Darkness to Light: Origin and Evolution of Young Stellar Clusters*, eds. T. Montmerle, P. André, ASP Conf. Series, Vol. 243, ASP, San Francisco, p. 255
- Feldman, W.C., Asbridge, J.R., Barne, S.J., Gosling, J.T.: 1977 in: *The Solar Output and its Variations*, ed. O.R. White, Ass. Univ. Press, Boulder, Colorado, p. 351
- Halbwachs, J.-L., Mayor, M., Udry, S., Arenou, F.: 2004, *Rev. Mex. A. A.*, 21, 20
- Holzer, T.E.: 1987, in: *Circumstellar matter*, IAU Symp. No. 122, eds. I. Appenzeller, C. Jordan, Reidel, Dordrecht, p. 289
- Gray, D.F.: 2005, *The Observations and Analysis of Stellar Photospheres*, 3rd Edition, Cambridge University Press, Cambridge
- Güdel, M., Guinan, E.F., Skinner, S.L.: 1997, *ApJ* 483, 947
- Kroupa, P.: 1995, *MNRAS* 277, 1522
- Kroupa, P.: 2002, *Science* 295, 82
- Kudritzki, R.P., Reimers, D.: 1978, *A&A* 70, 227
- Lang, K.R.: 1992, *Astrophysical Data. Planets and Stars*, Springer, Berlin
- Lim, J., White, S.M.: 1996, *ApJ* 462, 91
- Morax, E., Kroupa, P., Bouvier, J.: 2004, *A&A* 426, 75
- Mullan, D.J., Doyle, J.G., Redman, R.O., Mathioudakis, M.: 1992, *ApJ* 397, 225
- Perryman, M.A.C., Brown, A.G.A., Lebreton, Y., Gómez, A., Turon, C., Cayrel de Strobel, G., Mermilliod, J.C., Robichon, N., Kovalevsky, J., Crifo, F.: 1998, *A&A* 331, 81
- Raboud, D., Mermilliod, J.C.: 1998a, *A&A* 329, 101
- Raboud, D., Mermilliod, J.C.: 1998b, *A&A* 333, 897
- Sackmann, I. -J., Boothroyd, A.I.: 2003, *ApJ* 583, 1024
- Salpeter, E.E.: 1955, *ApJ* 121, 161
- Schmitt, J.H.M.M.: 1997, *A&A* 318, 215
- Stepień, K.: 1988, *ApJ* 335, 907
- van den Oord, G.H.J., Doyle, J.G.: 1997, *A&A* 319, 578
- Villanova, S., Baume, G., Carraro, G., Geminale, A.: 2004, *A&A* 419, 149
- Wargelin, B.J., Drake, J.J.: 2002, *ApJ* 578, 503
- Wood, B.E., Müller, H.-R., Zank, G.P., Linsky, J.L.: 2002, *ApJ* 574, 412
- Wood, B.E., Müller, H.-R., Zank, G.P., Linsky, J.L., Redfield, S.: 2005, *ApJ* 628, L143